Optimal flight parameters of unmanned helicopter for tea plantation frost protection

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Abstract: To determine proper flight parameters of an unmanned helicopter for tea plantation frost protection, field experiments were conducted to study the impact of flight height, speed and interval on airflow disturbance and temperature rise around tea canopies based on the analysis and simulation of frost protection with a certain helicopter. The relationship between temperature rise after flight and the above flight parameters was established through a regression orthogonal experiment, based on which the optimal combination of flight parameters was obtained through the single-factor golden section method. The results showed that wind speed around tea canopies decreased with the increase of flight height when flight speed was constant. There was a multivariate linear relationship between temperature rise and flight parameters, and the sequence of flight parameters' influence on frost protection effect was flight interval, flight height, flight speed. The optimal combination of flight parameters were flight height of 4.0 m, flight speed of 6.0 m/s and flight interval of 20 min. After the flight with the above parameters air temperature around tea canopies increased 1.6°C when background thermal inversion strength was 3.8°C.

Keywords: thermal inversion, frost protection, unmanned helicopter, flight parameters, orthogonal experiment, single-factor golden section method, tea plants
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1 Introduction

In the southern region of the Yangtze River, China, air temperature gradually rises in late spring, but drops rapidly in a short period of time once a sudden cold snap hits, which is often followed by occurrence of frost. Crops suffer from possible frost damage and the growth might be blocked, leading to yield and quality reduction[1,2]. The tea tree growing in this area is a thermophilic crop, particularly its early varieties. Late spring frost damage occurred frequently in recent years, which brought huge economic losses to growers[3-5]. Conventional frost protection measures like smudging, covering and flood irrigation are labor/time-consuming with poor effects[6,7]. Since 2007 frost protection wind machines were introduced to China and applied first in tea fields, which prevent frost damage by disturbing the thermal inversion layer above the crop. The machine is effective and automated with high cost and low utilization. Meanwhile its fixed installation limits the scope of protection area. To achieve efficient large-scale frost protection, the technology and equipment of mobile frost protection wind machines[13] and frost protection helicopters emerged[15,16].

Results from the test of frost protection with Sikorsky S-55-T-type helicopter in an orchard showed the best

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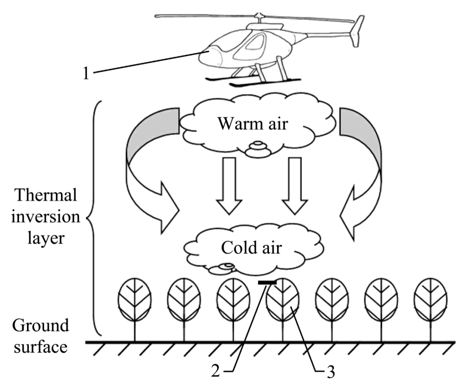
effect at flight speed of 11.11 m/s and flight interval of 10 min, which had nearly the same effect as wind machines[17]. Miller et al.[18] used 47G3B-1 helicopter for lemon frost protection and found that air temperature around the canopies increased as high as 3.3°C on a frost night when the thermal inversion strength was 7.8°C. It is reported that the flight of Mig-8 heavy helicopter under thermal inversion enabled maximum temperature rise around the canopy to reach half of the temperature difference between the flight height and the ground. It was the most effective to prevent frost at an altitude of 20-30 m and the flight speed of 5.56-8.33 m/s[19]. The above researches validated the feasibility of using helicopters for frost protection in agriculture, but the models are large manned helicopters with expensive purchase and running cost, which makes extension application difficult. With the rapid development of unmanned helicopters, the application in agricultural frost protection continued to expand[20-24]. The small unmanned helicopters are increasingly used for plant protection since they are light-weight, flexible in operation and easily fly at lower heights. Most applications are in the field of pesticide spraying. Hu et al.[23] utilized the airflow generated by unmanned helicopter rotors to spread out pollen, assisting hybrid rice pollination. To further expand the application of small unmanned helicopter in agriculture, crop frost protection could be achieved in frost-prone areas.

In China, Hu et al.[25] used a small unmanned helicopter for the first time to protect tea plants from frost damage. The effect of airflow disturbance was tested when the helicopter was hovering above the ground. The results showed that the helicopter made the largest disturbance to the ground within a hovering height range of 5-10 m, but the disturbance weakened with increasing hovering height. It also showed that air temperature around tea canopies increased by maximum of 3.83°C. In order to achieve better protection effects, it is necessary to determine the relationship between temperature rise and flight parameters in order to obtain the optimal combination of flight parameters.

The study simulated the process of frost protection with an unmanned helicopter based on the analysis of its working principle. Field experiments were conducted to find out the impacts of flight height, speed and interval on airflow disturbance, and the relationship between temperature rise around tea canopies and the above parameters was established to optimize the combination for better frost protection effects.

2 Frost protection principle of an unmanned helicopter

Normally air temperature near ground decreases with the increase of height, but late spring frost occurs within a certain height due to thermal inversion[1], which means air temperature increasing with the height. Air temperatures at 6 m and 9 m above tea fields were higher than the ground temperature by 4.4°C and 8.0°C respectively under temperature inversion[8-10]. Figure 1 shows an unmanned helicopter flying above the inversion layer in a tea field. The running rotors push warmer air aloft downwards to tea plants through convection to increase air temperature around tea canopies, and frost damage could be avoided or reduced. Real-time temperature is monitored with a temperature sensor at tea canopies to decide the start or stop of a flight. Inversion layer typically exists within a certain height above the ground, while airflow disturbance produced by the rotors of a helicopter is also limited by its flight height. Therefore, flight height is one of the important parameters of unmanned helicopters for frost protection. Furthermore, flight speed and flight interval also affect the frost protection effectiveness, efficiency and cost. Optimal combination of above flight parameters would be determined in this study.



1. Unmanned helicopter 2. Temperature sensor 3. Tea plants

Figure 1 Frost protection working principle of helicopter through airflow disturbance

The process of frost protection with an unmanned helicopter was dynamically simulated based on above analysis. The geometric model of the helicopter body and rotors was obtained through reverse engineering after 3-D scanning with a laser scanner (13SUMEC/ZB1349HK, EXAsan, Canada), and then put onto the top surface center of a cuboid shown in Figure 2, which was the given boundary of simulation space. The cuboid was 50 m long, 40 m wide and 16.5 m high with air inlet duct diameter of 4 m on the top surface, and the model grids were divided by Gambit and then imported into the CFD software (ANSYS, USA). The outlet was defined as a free one, and the inlet was a pressure one perpendicular to the rotors. The initial conditions were: air temperature of the inlet 6.85°C, the turbulence kinetic energy 0.02 m^2/s^2, the turbulent dissipation rate 0.008 m^2/s^3. Air temperature at the bottom of the cuboid (the location of the tea canopy) was set as −3.15°C. The physical property of the canopy was as follows: heat transfer coefficient 10 W/(m^2·K), the canopy thickness 0.2 m and the roughness 0.5.

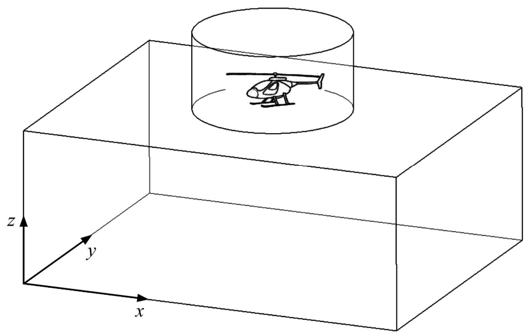


Figure 2 Calculation model of helicopter airflow disturbance

The post-processing tool (Tecplot, USA) was adopted to illustrate the simulation results in Figure 3. When rotation speed of the rotors was 1 300 r/min at a hovering height of 8 m, the canopy temperature of the horizontal cross-section decreased with the distance to the center. The width was 6 m and 3 m, within which air temperature rose above 0°C and 5°C, respectively. It was also found when the hovering height increased to 12 m, the temperature rose above 0°C within the width of 8 m, but temperature rise decreased within the width of 3 m.

Therefore, the application of unmanned helicopters for disturbing airflow on frost nights could effectively increase air temperature around tea canopies and achieve the desired frost protection effect.

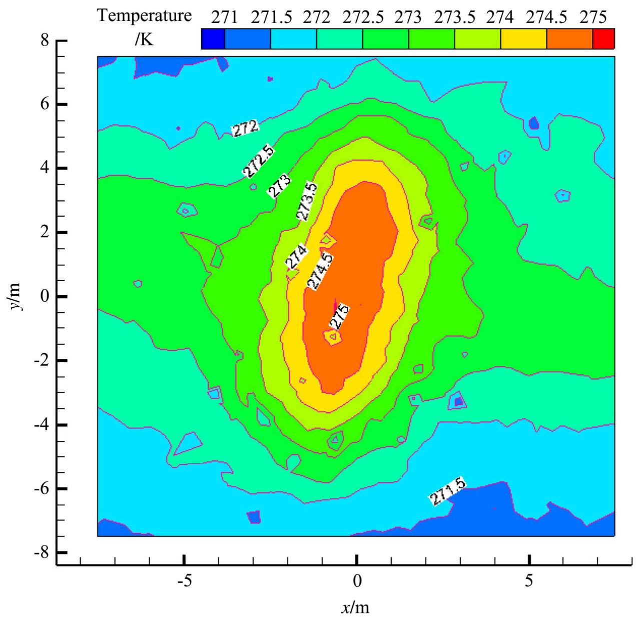


Figure 3 Simulation of temperature field distribution on a horizontal cross-section

3 Materials and methods

3.1 Materials

On March 13-14, 2014, the experiments were conducted on Maichun tea farm, which is located at latitude 32°01′35″N and longitude 119°40′21″E with a hilly terrain and an average altitude of 18.5 m. The tea variety of Jiukeng grew in the field, which was about 20 years old.

Figure 4 shows a spraying unmanned helicopter (CD-10, Hanhe, China) with the rotor diameter of 2 100 mm, flight speed of 0-8.0 m/s, takeoff weight of 35 kg.

Figure 4 Spraying unmanned helicopter used for tea plantation frost protection

And the other equipment and instruments used in the experiments were: six hot-wire anemometers (KIMO, France) with five one-way STV-150s and wind speed measurement accuracy of ±3%; four portable anemometers (NK4000, USA) with measurement accuracy of ±0.1 m/s and measurement range of 0.4-40.0 m/s; temperature recorders (ZDR-3W1S, Zeda, China) with measurement range of −40°C to 100°C and measurement accuracy of ±0.5°C.

3.2 Methods

3.2.1 Measurement of thermal inversion

The measurement of background thermal inversion was conducted from the night of March 13th to the morning of 14th, 2014 in the area without any influence of helicopter. As shown in Figure 5, a 15.0 m long pillar was set up vertical to the ground, and 9 ZDR-3W1S temperature recorders were arranged equidistantly along the pillar with the lowest one fixed at 0.2 m above the ground. The spacing was 2.0 m. The temperature recorders were set to collect air temperature every 10 min.

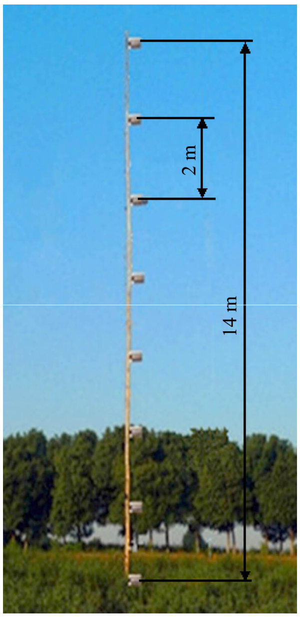


Figure 5 Temperature recorders setup in the field

3.2.2 Regression orthogonal test design

Based on the working principle analysis of unmanned helicopters for frost protection, the main factors which influence frost protection effects are: flight height, flight speed and flight interval. Their ranges were: 4.0-10.0 m for flight height, 1.0-6.0 m/s for flight speed and 20-50 min for flight interval. Temperature rise and wind speed at canopies after flight were selected as test indexes. In order to determine the significance order of the factors affecting frost protection effect and to establish the relationship between frost protection effect and the factors, the regression orthogonal test design was made[26], and correspondingly optimal flight parameters could be determined.

1) Factor- level coding

The levels of the above 3 factors were encoded to be equal in the coding space.

Zero level of canonical variables (Z_j) is expressed as:

$$Z_{0j} = \frac{Z_{1j} + Z_{2j}}{2} \tag{1}$$

The step length is:

$$\Delta_j = \frac{Z_{2j} - Z_{1j}}{2} \tag{2}$$

Then the coding formula is described as:

$$Z_j = \frac{x_j - x_{j0}}{\Delta_j} \quad j = 1,2,3 \tag{3}$$

Levels of the factors were coded according to Equation (3), shown in Table 1.

Table 1 Factor-level coding

Levels	Factors		
	Flight height x_1/m	Flight speed x_2/m·s^{-1}	Flight interval x_3/min
Upper level (+1)	10	6	50
Lower level (-1)	4	1	20
Zero level (0)	7	3.5	35
Step length Δ_j	3	2.5	15

2) Orthogonal table selection

The orthogonal table $L_8(2^7)$ was selected and the interaction among different factors was not considered. Three-variable linear regression orthogonal table is shown in Table 2. In order to improve the accuracy of the regression equation through loss of fit test, Treatments No. 8, 9 and 10 were arranged as zero-level repeatability tests.

Table 2 Orthogonal experiment arrangement

Treatments	Z_1	Z_2	Z_3
1	1	1	1
2	1	1	- 1
3	1	- 1	1
4	1	- 1	- 1
5	- 1	1	1
6	- 1	1	- 1
7	- 1	- 1	1
8	- 1	- 1	- 1
9	0	0	0
10	0	0	0
11	0	0	0

3) Test of frost protection flight

The test tea field was divided into 11 blocks of the same area for each treatment in Table 2. 6 ZDR-3W1S temperature recorders were placed on the tea canopy along the row of each test area to monitor temperature change before and after flight. The temperature rise was averaged with 6 collections. All treatments were done when frost appeared during the night of March 13-14, 2014.

3.2.3 Test of airflow disturbance to tea canopies

Temperature rise after the flight changes with the airflow disturbance produced by the helicopter. To find out the influence of airflow disturbance on tea canopies, another experiment was conducted with flight height (*H*) and flight speed (*V*) as factors and wind speed at canopies after flight as the index. The test arrangement and wind speed after flight are shown in Table 3.

Table 3 Disturbance test arrangements and results

Treatments	Factors		Wind speed after flight /m·s^{-1}
	Flight height/m	Flight speed/m·s^{-1}	
1	4	1	1.45
2	4	3.5	1.1
3	4	6	1.3
4	7	1	1
5	7	3.5	0.7
6	7	6	0.9
7	10	1	0.75
8	10	3.5	0.8
9	10	6	0.85

4 Results and analysis

4.1 Variation of thermal inversion

The natural wind speed during the test was low and varied in the range of 0-0.2 m/s. The minimum temperature reached −1.1°C and slight frost appeared. In the area without the influence of helicopter flight, air temperature variation is shown in Figure 6. The temperature dropped rapidly after sunset. Inversion existed from 17:00 to 6:00 in the morning. Then it disappeared around 7:00 due to the rapid rise of temperature. During the period of 22:00-5:30, tea canopy temperature fell below 0°C with frost being visible. During the period of 18:00-7:00, thermal inversion existed in the height of 0-14 m and the biggest inversion was 5.9°C, which appeared at 21:00. The result is nearly the same as previous study[27].

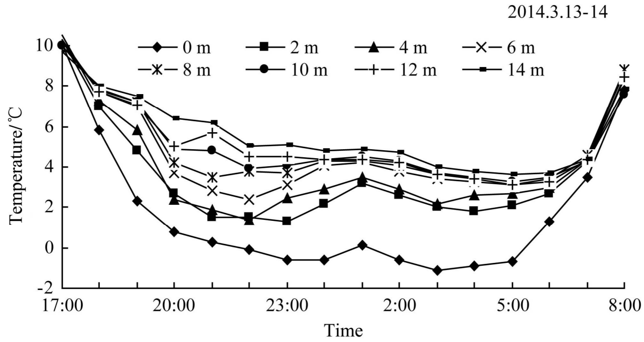


Figure 6 Air temperature variation on a frost night

The frost protection test with the helicopter flight was conducted from 4:40 to 5:50 and during this period the temperature difference between the ground and a height of 14.0m was 3.8°C.

4.2 Results and analysis of the flights

The results of 11 flights are shown in Table 4.

Table 4 Test results and statistics

Treatments	Z_0	Z_1	Z_2	Z_3	Temperature rise (y)/°C
1	1	1	1	1	0.78
2	1	1	1	- 1	1.5
3	1	1	- 1	1	0.6
4	1	1	- 1	- 1	0.65
5	1	- 1	1	1	1.1
6	1	- 1	1	- 1	1.6
7	1	- 1	- 1	1	1.03
8	1	- 1	- 1	- 1	1.3
9	1	0	0	0	0.92
10	1	0	0	0	0.85
11	1	0	0	0	0.75
$B_j=\Sigma z_j y_j$	11.080	-1.500	1.400	-1.540	
$b_j=B_j/M$	1.007	-0.188	0.175	-0.193	

4.2.1 Relationship between temperature rise and flight parameters

Regression coefficients of the three-variable linear equation were calculated using least square method. So the relationship between temperature rise (y) after the flight and flight parameters is described as

$$y = 1.007 - 0.188Z_1 + 0.175Z_2 - 0.193Z3 \quad (4)$$

Comparing the absolute value of the regression coefficients, it is obvious that the significance sequence of the factors is $x_3 > x_1 > x_2$, i.e., flight interval>flight height>flight speed.

4.2.2 Significance testing of the regression equation

Total regression sum of squares was

$$SS_T = \sum_{i=1}^{n} y_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} y_i\right) = 1.132$$

Factors' partial regression sum of squares were

$$SS_1 = m_c b_1^2 = 0.283$$

$$SS_2 = m_c b_2^2 = 0.245$$

$$SS_3 = m_c b_3^2 = 0.298$$

Regression sum of squares and residual sum of squares were

$$SS_R = SS_1 + SS_2 + SS_3 = 0.826$$

$$SS_e = SS_T - SS_R = 0.306$$

The results of significance testing are shown in Table 5.

Table 5 Analysis of variance

Sources of variance	*SS*	*df*	*MS*	*F*	significance
Z_1	0.283	1	0.283	6.432	**
Z_2	0.245	1	0.245	5.568	*
Z_3	0.298	1	0.298	6.773	**
Regression	0.826	3	0.275	6.250	**
Residual	0.306	7	0.044		
Sum	1.132	10			

Annotating: $F_{0.1}(1,7)$=3.59, $F_{0.05}(1,7)$=5.59, $F_{0.05}(3,7)$=4.35

The test statistics F in Table 5 were

F_1=6.432>$F_{0.05}$

F_2=5.568>$F_{0.1}$

F_3=6.773>$F_{0.05}$

F_R=6.250>$F_{0.05}(3,7)$

The result showed that flight height, flight speed and flight interval had significant influence on temperature rise, so Equation (4) was significant.

With the canonical variables replaced by the actual variables, the explicit equation with actual variables was described as

$$y = 1.603 - 0.063x_1 + 0.117x_2 - 0.013x_3 \quad (5)$$

4.2.3 Lack of fit test

Sums of squares for error of three zero-level treatments SS_{e1} and lack of fit SS_{Lf} were

$$SS_{e1} = \sum_{i=1}^{m_0} y_{0i}^2 - \frac{1}{m_0}\left(\sum_{i=0}^{m_0} y_{0i}^2\right)^2 = 0.0146$$

$$SS_{Lf} = SS_e - SS_{e1} = 0.2914$$

Corresponding degrees of freedom were

$$df_{e1} = m_0 - 1 = 2$$

$$df_{Lf} = df_e - df_{e1} = 6$$

And Lack of fit test F_{Lf} was

$$F_{Lf} = \frac{SS_{Lf} / df_{Lf}}{SS_{e1} / df_{e1}} = 8.093$$

Since F_{Lf}= 8.093<$F_{0.1}(5,2)$ = 9.33, the lack of fit was not significant. Therefore, Equation (5) fit very well with the actual situations.

Equation (5) was solved for its extremum with the single-factor golden section method[28]. The optimal solution was y=1.8 when x_1, x_2 and x_3 were 4.0, 6.0 and 20. Thus, the maximum temperature rise after flight was 1.8°C with flight height of 4.0 m, flight speed of 6.0 m/s and flight interval of 20 min.

4.3 Airflow disturbance to tea canopies

The wind speed around tea canopies after flight at different flight height and flight speed is shown in Table 3. Wind speed decreased with flight height at a certain flight speed. The higher the flight height was, the less airflow disturbance to tea canopies the helicopter produced, and consequently the worse frost protection could be caused.

The range analysis of wind speed is shown in Table 6. Compared with flight speed, the range of wind speed was is larger. Therefore, the influence of flight height on airflow disturbance is more than that of flight speed. Based on the sum of index for each factor at each level (K) and its average (k), the optimal combination was H_1V_3, i.e. flight height of 4.0 m and flight speed of 6.0 m/s. With the optimal flight parameters the flight brought about the largest airflow disturbance to the canopies. The optimal combination was consistent with the above optimal results of the maximum temperature rise. Therefore, the stronger airflow disturbance on the ground the flight produced, the better the protection effect became.

Table 6 Range analysis of wind speed

	Wind speed around tea canopies/m·s^{-1}	
	Flight height (H)	Flight speed (V)
K_1	3.85	2.2
K_2	2.6	2.6
K_3	2.4	3.05
k_1	1.283	0.733
k_2	0.867	0.867
k_3	0.8	1.017
Rang R	0.483	0.151
Optimal Combination	H_1V_3	

5 Conclusions

1) Orthogonal regression analysis indicated that there was a linear relationship between flight parameters (flight interval, flight height and flight speed) and air temperature rise around tea canopies. The significance sequence of flight parameters' influence on frost protection effect was flight interval, flight height, flight speed.

2) Solving the extremum of the regression equation through the single-factor golden section method, flight parameters combination for frost protection was optimized, and the optimal flight parameters were flight height of 4.0 m, flight speed of 6.0 m/s and flight interval of 20 min with the maximum temperature rise was 1.8°C.

3) At a certain flight speed, wind speed around tea canopies decreased as the flight height increased. At flight height of 4.0 m and flight speed of 6.0 m/s, wind speed increased to maximum of 1.45 m/s.

The frost was not severe during the experiment and maximum thermal inversion strength was only 3.8°C, which led to temperature rise of 1.6°C after the flight. Frost is an uncertain agricultural meteorological disaster, thus, thermal invention strength should be put into the model as a variable for future study to optimize the flight parameters for expanding the application occasion.

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